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On the Use of a Real-Time Control Approach for Urban Stormwater Management

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Abstract: The real-time control (RTC) system is a valid and cost-effective solution for urban stormwater management. This paper aims to evaluate the beneficial effect on urban flooding risk mitigation produced by applying RTC techniques to an urban drainage network by considering different control configuration scenarios. To achieve the aim, a distributed real-time system, validated in previous studies, was considered. This approach uses a smart moveable gates system, controlled by software agents, managed by a swarm intelligence algorithm. By running the different scenarios by a customized version of the Storm Water Management Model (SWMM), the findings obtained show a redistribution of conduits filling degrees, exploiting the whole system storage capacity, with a significant reduction of node flooding and total flood volume.

Keywords: sewer system; distributed real-time system; PID; multi-agent systems; gossip-based algorithm; rainfall-runoff; SWMM

1. Introduction

1.1. Background

As a significant urban infrastructure, combined sewer systems are characterized by complexity and management problems [1]. Nowadays, the relationship between the urban area and Urban Drainage System (UDS) is proving to be potentially damaging for the community and urban structures [2–4]. In this regard, the growth of impervious surfaces due to the ongoing urbanization led to a drastic change in the natural hydrological cycle, with a significant surface runoff [5–8]. Moreover, due to climate change, the intense rainfall phenomena amplify this issue [9,10], pushing the existing drainage networks beyond their capacity [11–14]. Therefore, the excess flow out of the sewer system intensifies the frequency and amplitude of critical phenomena such as local flooding and combined sewer overflows (CSOs), increasing the vulnerability of urban systems [13,15–17]. Urban flooding occurs when the UDS, being overloaded, enters a crisis by threatening property and infrastructure, with adverse consequences for human life, economic activities, and the environment [10,18]. This phenomenon is generally worsened by drainage networks' design inadequacy and incorrect and low maintenance.

Therefore, a transition from the conventional approaches towards innovative, sustainable, and smart strategies such as Low-Impact Development (LID) techniques and real-time control

(RTC) systems is necessary [19–33]. In this regard, recent scientific advances are focusing on the use of real-time control (RTC) approaches for the smart optimization of the urban drainage network. This technology's main advantage is to operate in real-time on the fluctuating conditions of the drainage systems, which are generally designed for a static load but operating under dynamic load. Usually, the drainage network's global capacity is not totally exploited (some system sections are poorly used or unused while others are overloaded) or is used in an inadequate way, preventing the achievement of the proper management of the system. The potential benefit of the RTC approach grows as well as the difference between the expected "design load" and the actual recorded "service load" [34]. The RTC system is a reliable and cost-effective methodology: it improves the hydraulic performance and helps the drainage system achieve its operational objectives [35–37], allowing temporary storage of rainwater volumes directly in existing networks and avoiding huge investments. The use of existing infrastructure for the outflow of wastewater and its control and management makes the economic feature a critical factor in choosing a RTC strategy. RTC cost efficiency is demonstrated by simulation studies [38] and by large-scale applications [39].

1.2. Real-Time Control Approach

In an urban drainage system, the RTC system allows to more easily achieve several operational objectives: minimization of overflow volumes and frequencies, flood prevention, management of discharge peaks to the wastewater treatment plant (WWTP), management of flows during a system disturbance (work deviations, equipment failures, or safety incidents), cost reduction, and other quality aspects [33].

The study carried out in Reference [40] shows that RTC in UDS is an efficient approach to improve performance and reduce the impact on the natural water environment. In recent years, theoretical studies (drainage system + RTC modeling) and technological innovations allowed the spread of RTC systems' implementation. Methodologies and equipment are available and well adaptable for different UDS uses [41]. The applicability of these devices has widened by recent developments in radar now-casting [42]; moreover, online measurements and available computational capacity have improved these tools' potential application field.

A RTC system dynamically regulates the drainage system, implementing a feedback loop based on online measurements to achieve specific operational objectives and improve the system's overall performance. Operational strategies and algorithms regulate the system operations according to the current state and dynamic network conditions detected in "real-time" [43]. A RTC system, equipped with specific devices (sensors, controllers, actuators), can coordinate multiple functionalities, such as (i) monitoring the current state of the network, (ii) comparing the current state against the wanted one, (iii) defining the settings of the control structures to achieve the wanted state, and (iv) determining the physical actions on the final control actuators. Thus, all the equipment allows the system's dynamic management according to the current conditions and the system's critical event [44].

The criteria to assess if a RTC strategy is suitable for a UDS are conditioned by several aspects, rather tricky to determine concerning the specific system features [45]. Several studies were carried out to establish the necessary standard and RTC application aspects. An example is the RTC guidelines [46] by the DWA (German Association for Water, Wastewater, and Waste). Moreover, some software tools were developed to support during the decision-making process, e.g., the planning tool called PASST (planning aid for sewer system real-time control) [38,46].

The critical analysis of the above factors allows the definition of a "control strategy". The RTC possible configurations range from simple and direct controls carried out at the "local" level (punctual or regional) to more complex "global" controls, concerning the whole system, with an "optimal predictive global" configuration [1].

So far, many studies were focused on a centralized RTC's approach [37,47,48]. However, given the huge amount of data to be read, managed, and processed, this type of control system, although reliable, presents some problems. Generally, in this approach, all data collected by sensors are sent to a central unit that produces the command for the actuators based on a specific strategy. Therefore, based on its functioning, a similar approach requires efficient connections among all elements (sensors and actuators) and a complex mathematical model. Moreover, one node's failure can compromise the whole system behavior [49].

Recently, Kändler et al. [50] have developed a new concept of a smart in-line storage system that does not need an advanced centralized control system, but it is easy to install and operates by real-time controlled actuators, and it can predict rainfall dynamics.

Moreover, among the literature studies on RTC developed in the last years, some have implemented control algorithms, without network online mathematical models. They use heuristic algorithms, based on externally imposed rules and previous knowledge of the drainage system (derived from experience and/or separate simulation procedures). The two most commonly used algorithms are Rule-Based Control (RBC) [51–53] and Fuzzy Logic Control (FLC) [54–60].

Other examples of optimization control algorithms' implementation, with mathematical network models, are run online to calculate set-points and determine control actions. These algorithms (reactive and predictive) are quite complex, especially the multi-objective control, which is the most frequent and focuses on the concept of Pareto optimal solution. The most commonly used optimization algorithms are the Linear-Quadratic Regulator (LQR) [61], the Evolutionary Algorithms (EA) [62–66], the Model Predictive Control (MPC) [67–78], and the Population Dynamics (PD) [79,80]. Studies focusing on implementing and validating specific software to simulate the RTC control systems' operation can be found in References [26,81–85].

1.3. Aims of the Study

From this literature analysis, some limitations about the application of a centralized real-time control approach emerge. Therefore, to overcome the previously highlighted limits, this study aims to show the hydrological efficiency of a distributed real-time control (DRTC) approach.

The hydrological behavior of a real drainage system of a highly urbanized area is modeled, and the hydrological response of uncontrolled and RTC-controlled scenarios under different rainfall events is investigated.

This approach aims to exploit the full storage conduits capacity in the drainage network using moveable and smart gates that, managed by the decentralized swarm intelligence algorithm (gossip-based), accumulate the excess stormwater volume in the system sections less overloaded.

The dynamic simulation model (with control) used, which works by customizing SWMM software that communicates in real-time with an external Java multi-agent software, was defined and tested in previous studies [49,86]. However, this study aims to take a step further than the previous ones by focusing on the optimal and most efficient moveable gates location analysis.

2. Materials and Methods

Based on the study's primary objective, a real-time distributed system control (DRTC) was considered to overcome the problems related to urban stormwater management. The whole methodology used to carry out the analysis, from the data retrieval useful for the hydrodynamic model development and then to the analysis of the system's criticalities, until the DRTC approach implementation and analysis of its efficiency, is summarized in the flowchart in Figure 1. At the same time, further details can be found in the following methodology's sub-sections.

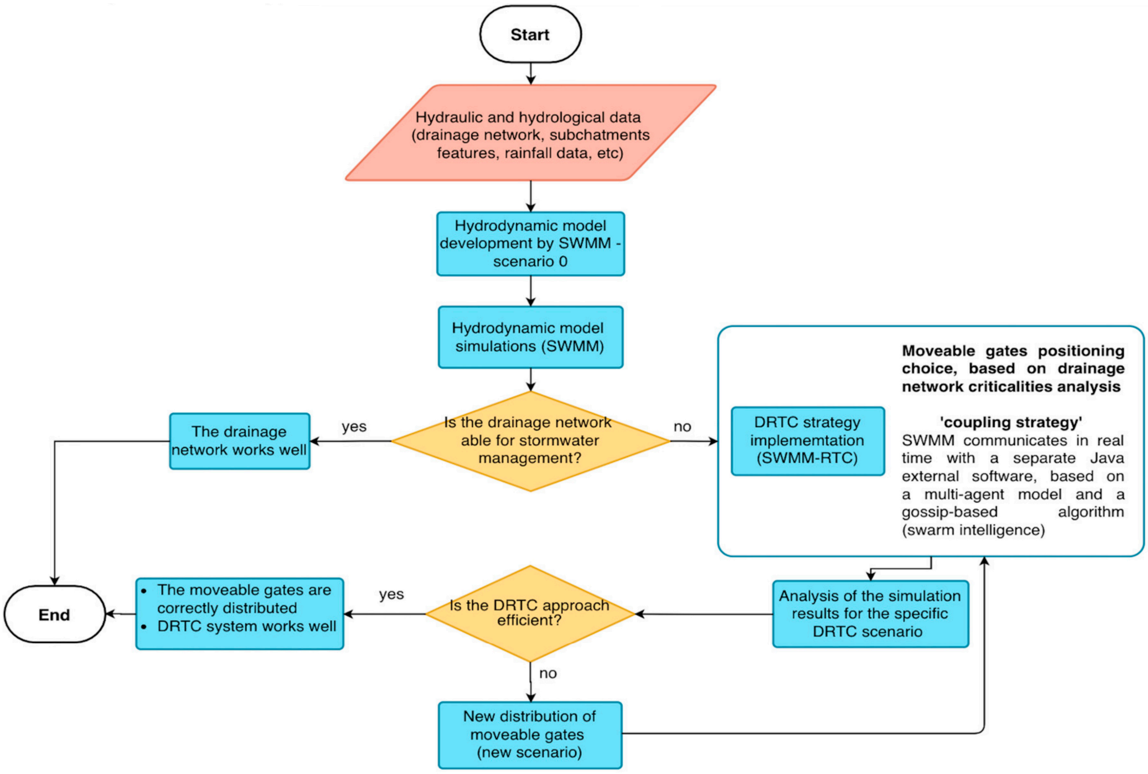

Figure 1. The flowchart of the methodology.

2.1. Case Study

In this study, the DRTC approach was applied to a highly urbanized district of an urban catchment located in Paola, Southern Italy (CS), in a Mediterranean climate region (Figure 2), characterized by hot, dry summers, and cool, wet winters.

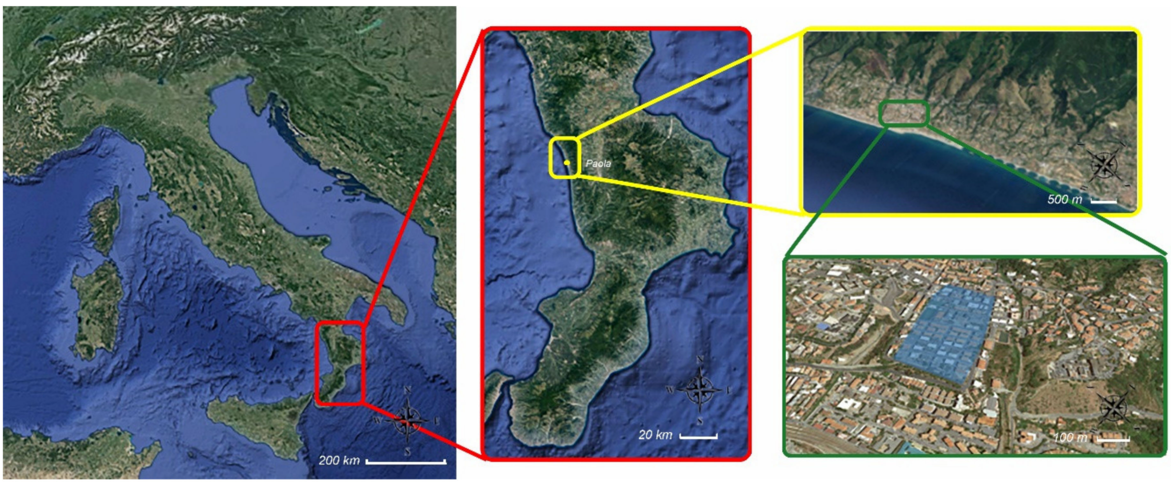

Figure 2. Case study location. A map of Italy with Calabria Region (**left**), the location of Paola village in Calabria Region (**middle**), and a zoom-in of Paola (in yellow box) and of the specific highly urbanized area considered as a case study (in green box) (**right**).

The general hydrological and hydraulic data and necessary information were taken from a previous study [87]. The specific area considered for the study is a highly urbanized area with a total area of 7.6 ha, out of which 96.0% are impervious, covered by roofing (28.9%), roads, parking lots, and other impermeable surfaces (67.1%), while only about 4.0% of the total surface area is a pervious area [87].

The drainage network, built at different times, is a combined sewer system that is not totally efficient due to frequent rainwater discharge into the sewer, low slopes, undersized conduits, etc. Therefore, the specific examined area reproduces the issues related to a general drainage system in a highly urbanized area, with the advantage that given its dimension, it can be modeled with greater detail. Based on the detailed information retrieved by the previous study [87] for the model development, it was possible to analyze the drainage network's criticalities, identify the best moveable gates location, and assess the distributed real-time control strategy efficiency.

2.2. Data Analysis

Design storms and measured rainfall events were considered to carry out the analysis.

More in detail, in the first phase, probabilistic analysis was conducted to determine the intensity–duration–frequency (IDF) curves for a Return Period (RP) of 1, 2, 3, 4, 5, 10, 20, 30, 40, and 50 years.

The IDF curves are generally considered a useful tool for standard hydrological risk analysis [88] and for the design, construction, and management process of several hydraulic engineering projects that present natural hazards due to extreme rainfall events [89].

The IDF curve represents a mathematical equation among rainfall intensity, duration, and return period [90]. More in detail, it can be expressed as $h(d, T) = a(T)d^n$ (where h is the precipitation height, d is the duration, T is the return period, while a(T) and n are two parameters, that have to be estimated by a probabilistic approach) [91] or based on the nomenclature we used as $PD_{D,RP} = aD^n$.

To define the IDF curve, it is necessary historical data of good quality, recorded for a continuous long time [90]. In this regard, for the specific case study, after the analysis of the available historical data for a long continuous period, the IDF relationships were computed by considering the historical records (collected between 1945 and 2005) of the annual maximum series for rainfall durations of 1, 3, 6, 12, and 24 h (obtained from the Regional Environmental Protection Agency of Calabria (ARPACAl) [92], Paola site, cod. 3060). To develop the IDF curve, the Gumbel extreme values distribution was used as cumulative probability function; for each duration and selected return periods, the rainfall depths were calculated and the least-square method was considered to determine the parameters (a and n) of the empirical IDF. The rainfall depth reported in a graph (PD, D) were interpolated by the power function previously described, identifying the IDF curve. More detail on the procedure used to develop the IDF curve can be found in References [90,91].

Based on the defined IDF relationship, the Chicago Hyetographs, proposed by Reference [93] to evaluate the design rainfall for the urban sewer system, was calculated. More in detail, this design storm event, based on two analytical equations, one valid before the peak position and the other after it, was chosen to generate a synthetic rainfall event with the maximum intensity. Therefore, to evaluate the system's response under different design storms, in this study, starting from the IDF curves of 5, 10, and 20 years return periods, the Chicago Hyetographs of 1 h were developed.

In the second phase, to select recorded rainfall events, 5 min cumulative rainfall series collected from May 2019 to May 2020 on the Paola rain gauge ([92] Paola site, cod. 3060) was considered. More in detail, from all collected data, the individual events were defined as being separated by a continuous dry period of at least six hours, and only the events with a precipitation depth greater than 2 mm were selected [94–96].

Therefore, for each selected rainfall event, the hydrological characteristics in terms of precipitation depth (PD), rainfall duration (D), and rainfall intensity (i) were evaluated.

Moreover, since the IDF curves gave information of the frequency of extreme rainfall events for a variety of durations and intensities, the selected measured rainfall events were compared with the historical records obtained from the Regional Environmental Protection Agency of Calabria (ARPACAl) through the intensity–duration–frequency (IDF) previously obtained. At the end of this analysis, only the most significant rainfall events that caused the specific drainage network crises were considered for the RTC simulations.

2.3. The Distributed Real-Time Control Approach

In this study, a real-time distributed system control (DRTC) approach was used. The methodology used involves the use of a specific dynamic simulation model with control. This real-time control strategy refers to the model defined and tested in previous studies [49,86]. The model was created with customization of the Storm Water Management Model (SWMM) (provided by EPA [45] as a hydrodynamic model), to communicate in real-time with a separate Java external software, based on a multi-agent model and a gossip-based algorithm (swarm intelligence).

However, although SWMM allows some real-time control of the parameters of the network (by defining some simple rules, if-then-else), through the "coupling strategy," the method exploits the potential of the two different software to achieve better system performance and to adjust the hydraulic network parameters dynamically in real-time.

The overall control was distributed over a nodes network, and it was realized using a multi-agent paradigm and a swarm intelligence algorithm. These algorithms define simple entities' behavior, interacting with each other, produce an emerging property [97]. Thus, simple entities are represented by agents "intelligent" gates and the emerging property is the balancing of conduit capacities to optimize the adequate sewer network storage capacity.

The algorithm structure presents adaptivity and fault-tolerance properties since the procedure's iterativity ensures that convergence [98] cancels the effect of unforeseen events.

In a real case, to achieve the proposed goals, the network requires the effective distributed implementation of hardware elements, as explained in References [49,86]: sensors, one water level sensor per conduit and a flow sensor on the outfall, computational nodes, which can host and execute the distributed control algorithm, and down-hinged moveable gates, which can be real-time-regulated electronically.

The study carried out by the authors of References [49,86] explains that computational nodes, distributed throughout the network, dynamically regulate the gates according to the information acquired by the sensors in the neighbor areas. Each computational node has a partial view of the network as it can read only from the sensors and actuate only on the gates which can physically reach (peer-to-peer communication). After data reading, the nodes collectively process the acquired information to trigger suitable activation on the gates. The collective computation of the network of nodes supplies the gates with "intelligent" behavior.

The algorithm consists of balancing the water level perceived by the agents. This balance is obtained by the agents that perform two tasks in a repeated sequence: (i) estimate the average water level in the network (gossip-based algorithm), and (ii) properly adjust the specific gate to bring the water level as close to this average as possible.

The gates, mobile and electronically operable, can manage the conduits' capacity by a Proportional Integrative Derivative (PID) controller [86]. A PID controller consists of a control loop that minimizes an error value consisting of the difference between controlling the process' output and the desired value (set-point). Through an electromechanical action on the plate, the gates opening degree, as the water flow at the network's points where the gates are located, is modified based on a "desired" value.

This methodology exploits full storage conduits capacity by accumulating the excess stormwater volume in the system's less overloaded parts.

2.4. Modeling Scenarios

To evaluate the DRTC's hydraulic performance, the drainage network's response was modeled by considering different scenarios, depending on moveable gates' number and positions across the network.

Scenario 0, or reference scenario, corresponding to the uncontrolled drainage system's current situation, was modeled as reported in Reference [87]. The model area was subdivided into 26 sub-catchments, while the drainage network was modeled by considering 29 nodes and 28 conduits modeled. The network presents variability in conduits' geometry and materials: concrete conduits with rectangular cross-section of different sizes (diameters 400 × 400 mm and 450 × 450 mm) and stoneware conduits presenting a circular cross-section (diameters of 200 and 300 mm).

To model Scenarios 1 and 2, the software deriving from the SWMM customization with the specific control algorithm (called SWMM-RTC), previously described, was considered. The use of this software has required the network re-modeling, with the introduction of smart moveable gates, modeled in SWMM as a transverse weir with the opening area equal to the conduit section area. More in detail, as shown in Figure 3, Scenario 1 was modeled by applying moveable gates in all conduits, while Scenario 2 presents specific control, with the gates located on the main network, downstream of each sub-network, at the points where the network branches (sub-networks) engage in the main channel.

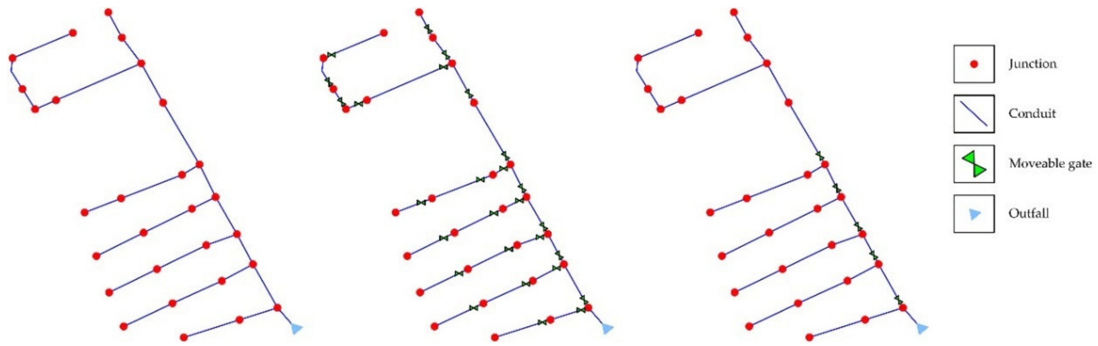

Figure 3. Drainage network schematization. From left to right: Scenario 0, Scenario 1, and Scenario 2.

The Soil Conservation Service (SCS) Curve Number (CN) method was used for the infiltration assessment. More in detail, for the CN estimation, based on the retrieved data for each sub-catchment, the values tabulated in Reference [99] were considered, while the flow routing computations were based on the Dynamic Wave Equations.

2.5. Hydrological Performance Indicators

To evaluate the beneficial effect of the use of the DRTC approach, the results in terms of node flooding (NF), total hours flooded (HF) by nodes, total flood volume (FV), and conduit surcharge (CS) were analyzed, and the performance indicators, reported below, were estimated.

(1) Flood Volume Reduction (FVR_{n-m}) was expressed as the percentage difference between the total Flood Volume (FV) of n and m scenarios:

$$FVR_{n-m}\,(\%) = \frac{FV_n - FV_m}{FV_n} \times 100 \tag{1}$$

(2) Hours Flooded Reduction (HFR_{n-m}) was determined as the percentage difference between the Hours Flooded (HF) of n and m scenarios:

$$HFR_{n-m}(\%) = \frac{HF_n - HF_m}{HF_n} \times 100 \tag{2}$$

(3) The percentage of nodes flooding (NF_n) was calculated concerning the total number of nodes (NN_{tot}):

$$NF_n\,(\%) = 100 - \frac{NN_{tot} - NF_n}{NN_{tot}} \times 100 \tag{3}$$

(4) The percentage of conduit surcharge (CS_n) was evaluated concerning the total number of conduits (NC_{tot}):

$$CS_n(\%) = 100 - \frac{NC_{tot} - CS_n}{NC_{tot}} \times 100 \quad (4)$$

Moreover, to analyze the balancing of the flow within the drainage system for the network branches (sub-networks) and the main channel, a comparative analysis of the conduit's filling degree was carried out by graphs showing the conduit's capacity trend over time.

3. Results and Discussion

3.1. Rainfall Events

The design storm events (Chicago Hyetographs), determined as discussed in Section 2.2, present a rainfall duration of 1 h and a return period of 5, 10, and 20 years, with total precipitation of 70.9, 81.6, and 91.9 mm, respectively. The model was first run by considering these three extreme rainfall events characterized by short duration and high intensity to evaluate its efficiency.

While, concerning the evaluation of the recorded rainfall events, as reported in Table 1, the whole studied period was characterized by 54 rainy events, for a total precipitation depth (PD) of 923.4 mm ranging from 2.0 to 105.2 mm with a mean value of 17.1 mm. For the whole dataset: 46.3% of the rainfall events had a precipitation depth less than 10 mm, 25.9% had a precipitation depth between 10 and 20 mm, 7.4% had a precipitation depth between 20 and 30 mm, 11.1% had a precipitation depth between 30 and 40 mm, 5.6% had a precipitation depth between 40 and 50 mm, 1.9% (one event) had a precipitation depth of 74.6 mm, and one event had a precipitation depth of 105.2 mm.

Table 1. Hydrological characteristics of each rainfall event recorded from May 2019 to May 2020. PD: precipitation depth, D: rainfall duration, Mean i: mean rainfall intensity, and Max i: maximum rainfall intensity.

No.	Date (day/month/year)	(hour:minute)	PD (mm)	D (h)	Max i (mm/h)	Mean i (mm/h)
1	04/05/2019	08:00	31.4	6.58	24	4.8
2	06/05/2019	06:00	4.8	1.58	9.6	3.0
3	12/05/2019	05:00	2.8	0.92	4.8	3.0
4	13/05/2019	00:00	16.2	1.5	43.2	10.8
5	15/05/2019	23:00	8.8	2.0	21.6	4.4
6	28/05/2019	02:00	9.4	2.5	21.6	3.8
7	01/06/2019	01:00	7.2	2.0	7.2	3.6
8	16/07/2019	01:00	31.0	2.08	57.6	14.9
9	02/09/2019	18:00	13.2	0.83	50.4	15.9
10	08/09/2019	11:00	21.6	1.25	45.6	17.3
11	19/09/2019	13:00	7.8	1.08	33.6	7.2
12	24/09/2019	02:00	4.0	0.5	4.8	8.0
13	26/09/2019	14:00	14.6	1.66	52.8	8.8
14	03/10/2019	04:00	10	1.92	16.8	5.2
15	05/10/2019	13:00	17.4	3.42	16.8	5.1
16	07/10/2019	06:00	40.6	3.75	76.8	10.8
17	16/10/2019	08:00	4.2	0.33	28.8	12.7
18	31/10/2019	19:00	4.2	1.25	4.8	3.4
19	04/11/2019	01:00	11.4	2.42	24.0	4.7
20	06/11/2019	13:00	33.2	6.58	21.6	5.0

Table 1. *Cont.*

No.	Date (day/month/year)	(hour:minute)	PD (mm)	D (h)	Max i (mm/h)	Mean i (mm/h)
21	09/11/2019	07:00	32.2	5.17	31.2	6.2
22	11/11/2019	19:00	17.00	4.08	26.4	4.2
23	13/11/2019	00:00	21.0	3.42	31.2	6.1
24	17/11/2019	07:00	34.0	4.17	43.2	8.2
25	19/11/2019	18:00	24.6	4.75	19.2	5.2
26	24/11/2019	07:00	74.6	12.25	33.6	6.1
27	28/11/2019	05:00	16.2	2.17	38.4	7.5
28	06/12/2019	04:00	3.4	1.25	4.8	2.7
29	07/12/2019	01:00	7.4	0.75	21.6	9.9
30	09/12/2019	12:00	18.4	3.67	9.6	5.0
31	12/12/2019	02:00	42.2	8.83	36.0	4.8
32	20/12/2019	03:00	3.2	0.92	7.2	3.5
33	21/12/2019	08:00	12.2	3.33	7.2	3.7
34	22/12/2019	00:00	12.4	3.08	12	4.0
35	25/12/2019	02:00	5.2	1.42	7.2	3.7
36	18/01/2020	10:00	11.0	24.0	16.8	0.5
37	29/01/2020	20:00	3.4	1.0	16.8	3.4
38	02/02/2020	03:00	2.8	1.08	4.8	2.6
39	05/02/2020	02:00	2.4	0.58	12.0	4.1
40	10/02/2020	07:00	4.2	1.67	4.8	2.5
41	14/02/2020	12:00	5.8	1.08	12.0	5.4
42	20/02/2020	00:00	4.8	0.75	19.2	6.4
43	28/02/2020	02:00	7.0	1.83	14.4	3.8
44	03/03/2020	02:00	21.0	5.67	21.6	3.7
45	04/03/2020	20:00	3.6	0.5	9.6	7.2
46	07/03/2020	11:00	16.6	4.33	9.6	3.8
47	22/03/2020	10:00	4.0	1.5	4.8	2.7
48	25/03/2020	04:00	105.2	24.5	19.2	4.3
49	01/04/2020	04:00	8.0	1.33	12.0	6.0
50	03/04/2020	06:00	6.2	2.25	4.8	2.8
51	20/04/2020	02:00	15.6	5.33	7.2	2.9
52	21/04/2020	22:00	47.6	9.08	36.0	5.2
53	19/05/2020	15:00	4.2	1.58	4.8	2.7
54	20/05/2020	11:00	32.2	3.58	31.2	9.0
		Maximum	105.2	24.5	76.8	17.3
		Minimum	2.4	0.33	4.8	0.5
		Mean	17.1	3.6	21.4	5.8
		Sum	923.4	195.05		

Figure 4 compares all the 54 recorded rainfall events, in terms of total rainfall depth and duration, with the intensity–duration–frequency (IDF) curves. By analyzing this figure, it emerges that most of the rainfall events fall below the one-year return period threshold, eight events present a return period greater than one year, with one greater than two years, one on the ten-year IDF curve, and one relatively near to the 40-year threshold.

The critical real rainfall events, whose hydrological characteristics are summarized in Table 2, were considered to analyze the different scenarios.

First, a comparative evaluation analysis in terms of precipitation depth, mean rainfall intensity, and maximum rainfall intensity was carried for the whole dataset. This analysis was principally based on the different hydrological parameters' influence on the sewer system's response. For instance, after a first analysis, the rainfall event with a maximum precipitation depth of 105.2 mm (occurred 25 March 2020) and a mean intensity of 2.2 mm/h did not provide local flooding phenomena. Then, all events with a mean intensity higher than its average value (5.8 mm/h) were considered, obtaining that only the seven rainfall events shown in Table 2 caused network criticalities in terms of node flooding volume for Scenario 0.

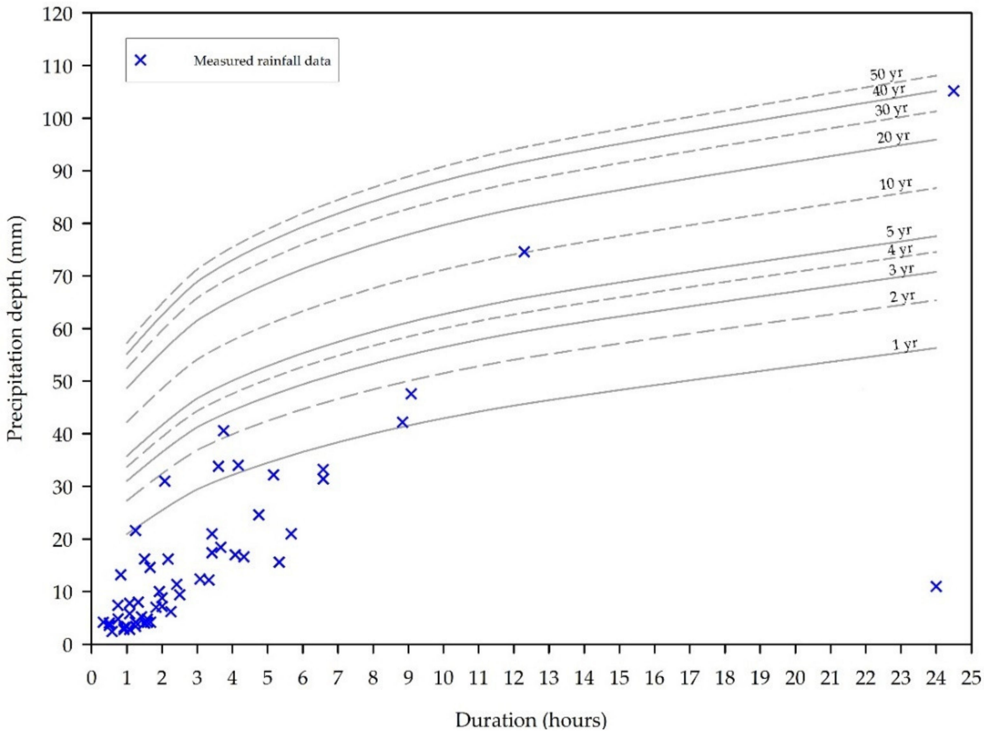

Figure 4. Rainfall characteristics for the 12-month data series (54 measured rainfall data between May 2019 and May 2020) compared with the intensity–duration–frequency (IDF) return period curves estimated for Paola (CS).

Table 2. Rainfall events for simulations.

No.	Date (day/month/year)	PD (mm)	D (h)	Max i (mm/h)	Mean i (mm/h)
1	13/05/2019	16.2	1.5	43.2	10.8
2	16/07/2019	31	2.08	57.6	14.9
3	08/09/2019	21.6	1.25	45.6	17.3
4	07/10/2019	40.6	3.75	76.8	10.8
5	17/11/2019	34	4.17	43.2	8.2
6	24/11/2019	74.6	12.25	33.6	6.1
7	20/05/2020	32.2	3.58	31.2	9

Moreover, by analyzing the hydraulic response of the uncontrolled scenario, it was noted that all seven events had a maximum rainfall intensity higher than the average value of the same parameter (21.4 mm/h) for the whole dataset and a precipitation depth higher than the average value (17.1 mm).

3.2. *DRTC Approach Efficiency*

To evaluate the hydrological performance of the real-time control approach applied in both scenarios (1 and 2), the models' response, run by considering a total of 10 rainfall events, including the three designs storm events and the seven real ones, was analyzed.

The findings obtained by considering the design storm events, in terms of the number of Node Flooding (NF), Hours Flooded (HF), Conduit Surcharge (CS), and total Flood Volume (FV) for each scenario and each design rainfall event, are shown in Table 3.

Table 3. Node Flooding (NF), Hours Flooded (HF), Conduit Surcharge (CS), and total Flood Volume (FV) for each scenario (S0, S1, S2) and each design rainfall event of 5, 10, and 20-year return periods (RP).

	RP = 5 Years			RP = 10 Years			RP = 20 Years		
	S0	**S1**	**S2**	**S0**	**S1**	**S2**	**S0**	**S1**	**S2**
NF (-)	12	6	5	12	8	7	12	8	7
HF (h)	3.87	1.07	0.49	4.43	1.63	0.96	4.89	2.09	1.13
CS (-)	19	8	7	19	10	9	19	12	9
FV (10^6 L)	0.88	0.19	0.04	1.08	0.33	0.09	1.28	0.49	0.14

By analyzing Table 3 emerges, as expected, growing values of hours flooded and total flood volume as the return period increases.

By comparing the different scenarios for the same return period, it is possible to observe an improvement of the drainage network efficiency with relevant mitigation of flooding produced using a distributed real-time control approach.

Based on the results obtained in Table 3, the performance indexes were evaluated as described in Section 2.5, obtaining the findings described in Tables 4–7.

Tables 4 and 5 report the results obtained in terms of Flood Volume Reduction (FVR_{n-m}) and Hour Flooded Reduction (HFR_{n-m}), assessed by comparing the uncontrolled scenario (Scenario 0) with the two real-time controlled scenarios (Scenarios 1 and 2) and then comparing the two controlled scenarios with each other.

Table 4. Flood Volume Reduction (FVR) index for design storm events.

RP	**FVR (%)**		
	FVR_{0-1}	**FVR_{0-2}**	**FVR_{1-2}**
5 years	78.41	95.45	78.95
10 years	69.44	91.67	72.73
20 years	61.72	89.06	71.43

Table 5. Hour Flooded Reduction (HFR) index for design storm events.

RP	**HFR (%)**		
	HFR_{0-1}	**HFR_{0-2}**	**HFR_{1-2}**
5 years	72.35	87.34	54.21
10 years	63.21	78.33	41.1
20 years	57.26	76.89	45.93

While, the results obtained for the third performance indicator (NF), which represents a percentage measure of the number of nodes flooding compared to the total node number, are shown in Table 6.

Table 6. Nodes flooding (NF) index for design storm events.

RP	**NF (%)**		
	NF 0	**NF 1**	**NF 2**
5 years	41.38	20.69	17.24
10 years	41.38	27.59	24.14
20 years	41.38	27.59	24.14

The results in terms of conduit surcharge for each scenario and design storm event are shown in Table 7.

Table 7. Conduit surcharge (CS) index for design storm events.

RP	CS (%)		
	CS 0	CS 1	CS 2
5 years	67.86	28.57	25.00
10 years	67.86	35.71	32.14
20 years	67.86	42.86	32.14

The findings show that real-time controlled scenarios, 1 and 2, present higher efficiency than the uncontrolled scenario (Scenario 0), achieving the best performance for Scenario 2, where the movable gate's location was defined after the drainage network hydraulic conditions analysis.

Based on this finding, the analysis was carried out for the seven critical recorded rainfall events by comparing only the uncontrolled Scenario 0 and the real-time controlled Scenario 2, which had presented the better performance indexes for the design storm events. In this regard, Table 8 shows the results obtained in terms of Node flooding (NF), Hours flooded (HF), Total Flood Volume (FV), and Conduits Surcharge (CS) parameters.

Table 8. Node Flooding (NF), Hours Flooded (HF), total Flood Volume (FV), and Conduits Surcharge (CS) for Scenario 0 (S0) and Scenario 2 (S2).

No.	NF (-)		HF (-)		FV (10^6 L)		CS (-)	
	S0	S2	S0	S2	S0	S2	S0	S2
1	5	0	1.55	0.00	0.14	0.00	14	1
2	8	1	5.62	0.01	0.96	0.00	15	5
3	6	0	3.85	0.00	0.35	0.00	14	1
4	4	0	1.55	0.00	0.10	0.00	14	1
5	6	0	4.22	0.00	0.40	0.00	14	1
6	4	0	1.56	0.00	0.2	0.00	14	1
7	6	0	2.94	0.00	0.26	0.00	14	1

By analyzing Table 8, it emerges that Scenario 2 does not only improve the network hydraulic performance but also achieves maximum efficiency in terms of the total reduction of the number of nodes flooding and a considerable reduction of surcharge conduits.

Finally, to evaluate the balancing of the flows within the drainage network, achieved by using the RTC strategy, a comparative analysis was carried out by considering that the filling degree of each conduit belongs to the individual sub-network and the main network. In this regard, the graphs showing the conduit capacity trend over time for RP of 10 years and each scenario are reported in Figure 5 for four conduits (6, 8, 10, and 27) and in the Appendix A (Figures A1–A8) for all conduits.

These figures confirm that by implementing RTC control strategies (especially in Scenario 2, specific control), achieving a relevant improvement of the drainage network performance is possible. This efficiency is obtained in terms of overflow attenuation and reducing the overflow duration (as shown for conduits 6 and 8 in Figure 5) with a simultaneous capacity of flow stationing inside conduits for a long time (for instance, conduits 27, 6, and 8 in Figure 5; for graphic reasons, the simulation was stopped at one day). While for conduit 10 in Figure 5, it is observed at an almost total reduction of flow.

Observing the graphs for all conduits, a flow balancing with a redistribution of the filling degree within the whole drainage system emerges, which is often below the threshold value of 0.75 in Scenario 2. This significant finding was achieved by exploiting all sewer system reservoir capacity by involving the flows from the overloaded conduits to those less charged. Moreover, in some conduits, a reduction and delay of the peak capacity were achieved.

Table 2 is the best for flow balancing and total flooding volume reduction. Moreover, this scenario also presents considerable economic benefits, with a lower cost of implementation due to the fewer moveable gates installed than in Scenario 1.

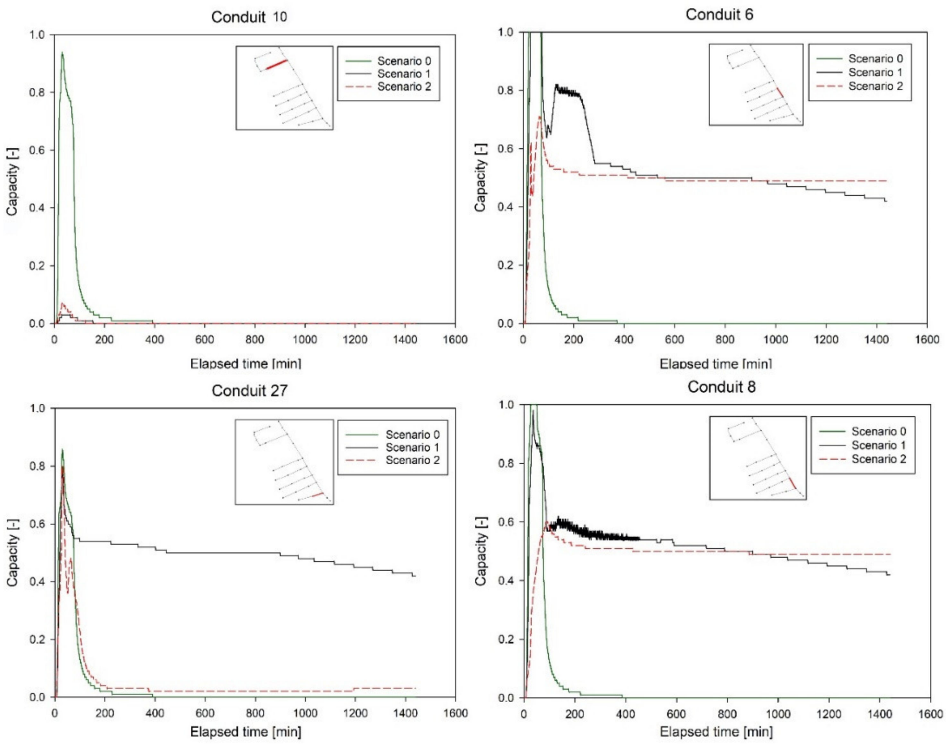

Figure 5. The drainage network response, in terms of conduits capacity over the time, to the design storm event (RP = 10 years) for each modeled scenario.

4. Conclusions

Real-time control strategies applied to an existing drainage network represent a solution for optimizing urban stormwater management and minimizing urban flooding risk.

In this study, the behavior of a real drainage network of a highly urbanized area was modeled, and the hydrological response of uncontrolled and RTC controlled scenarios to different extreme rainfall events was analyzed. A distributed real-time control (DRTC) system, defined and tested in previous studies, was used to achieve the aim. This approach was created by customizing SWMM software that communicates in real-time with an external Java multi-agent software. To exploit all conduits' reservoir capacity in the drainage network, moveable and smart gates, controlled by software agents, managed by a decentralized swarm intelligence algorithm (gossip-based), were implemented in the model.

The results demonstrated the DRTC approach's validity in system control. A conduit filling degree redistribution, in many cases below 75%, was achieved. Moreover, for some events, a reduction and delay of peak capacity was observed. The CS and NF indicators showed positive findings, with a generalized decrease in conduits' overload and node flooding. The flow balancing also produced its effects on $FVR_{n\text{-}m}$ and $HFR_{n\text{-}m}$ indexed reduction, assessed by comparing the scenarios. Scenario 2 achieved the maximum hydrological efficiency for the system in terms of a complete reduction in the number of flooding nodes and an acceptable reduction of surcharge conduits.

Therefore, analyzing the main findings produces a positive qualitative evaluation of the DRTC approach in terms of network hydraulic performance efficiency and environmental vulnerability reduction. This approach allows a significant increase in the system flexibility to react to unexpected scenarios.

Finally, the economic aspect is also crucial for the RTC system choice. This approach allows a general system performance improvement and reduces critical issues, avoiding significant and costly investments through existing infrastructure reorganization.

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Appendix A

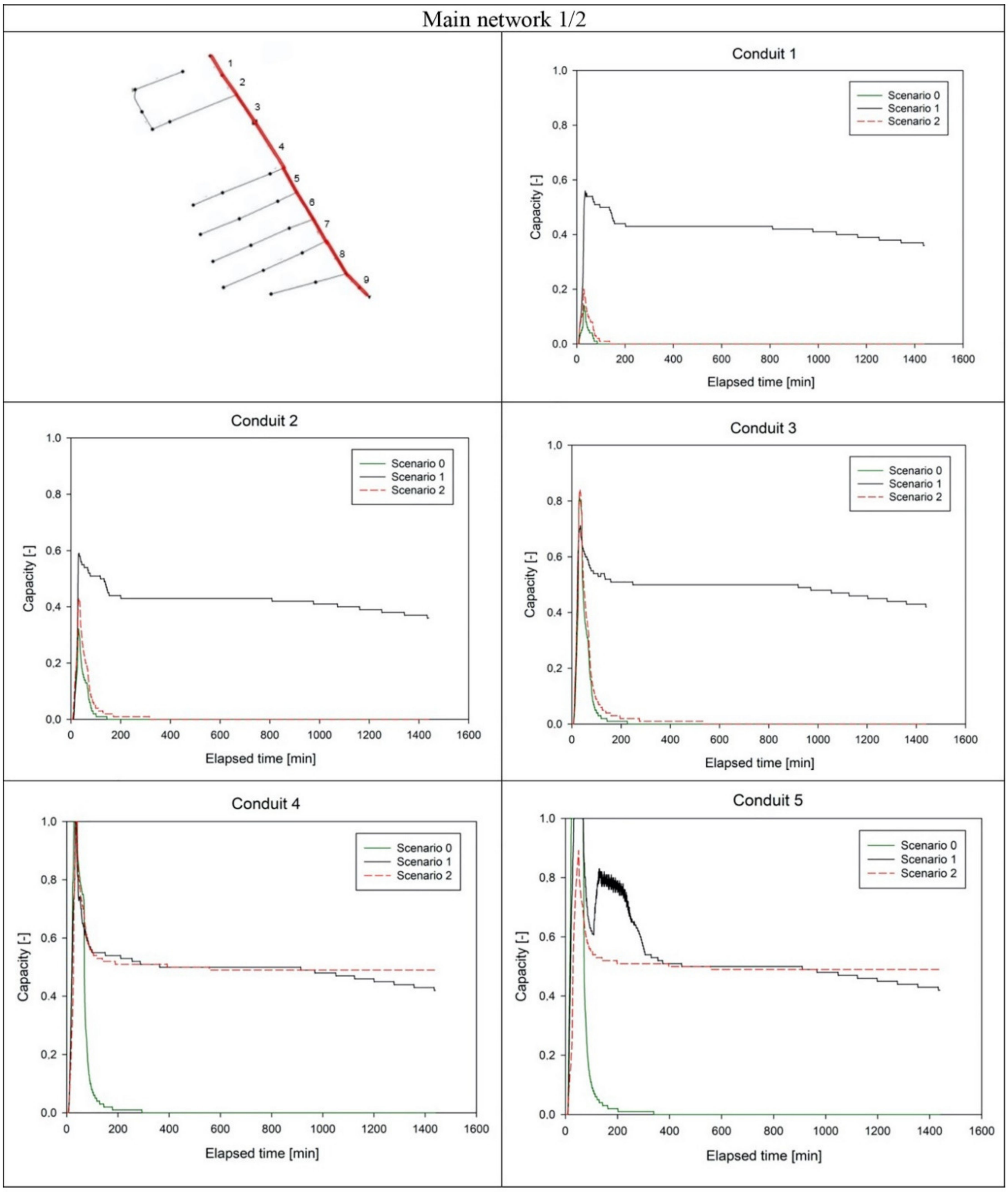

Figure A1. Conduits' capacity in the main network, highlighted in red in the first picture where the drainage network schematization is shown.

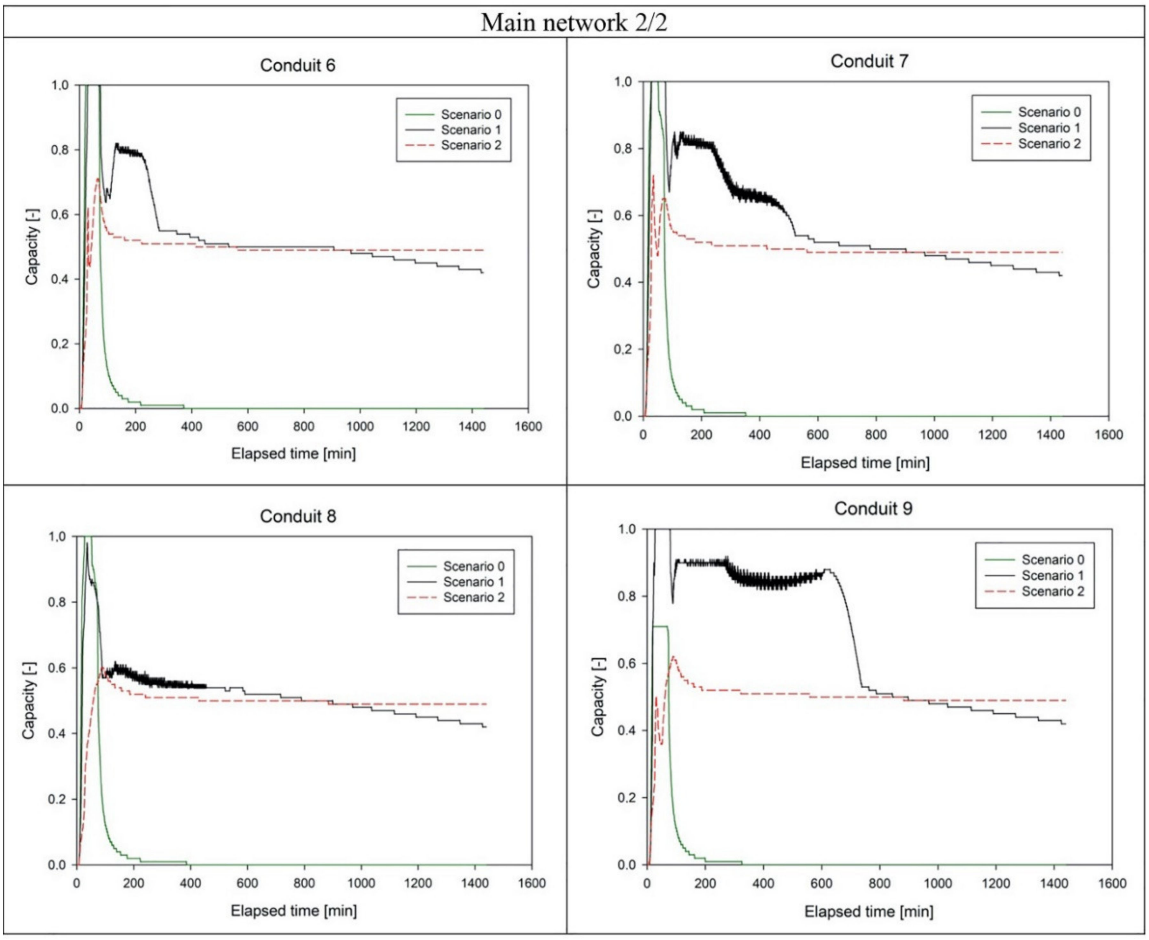

Figure A2. Conduits' capacity in the main network.

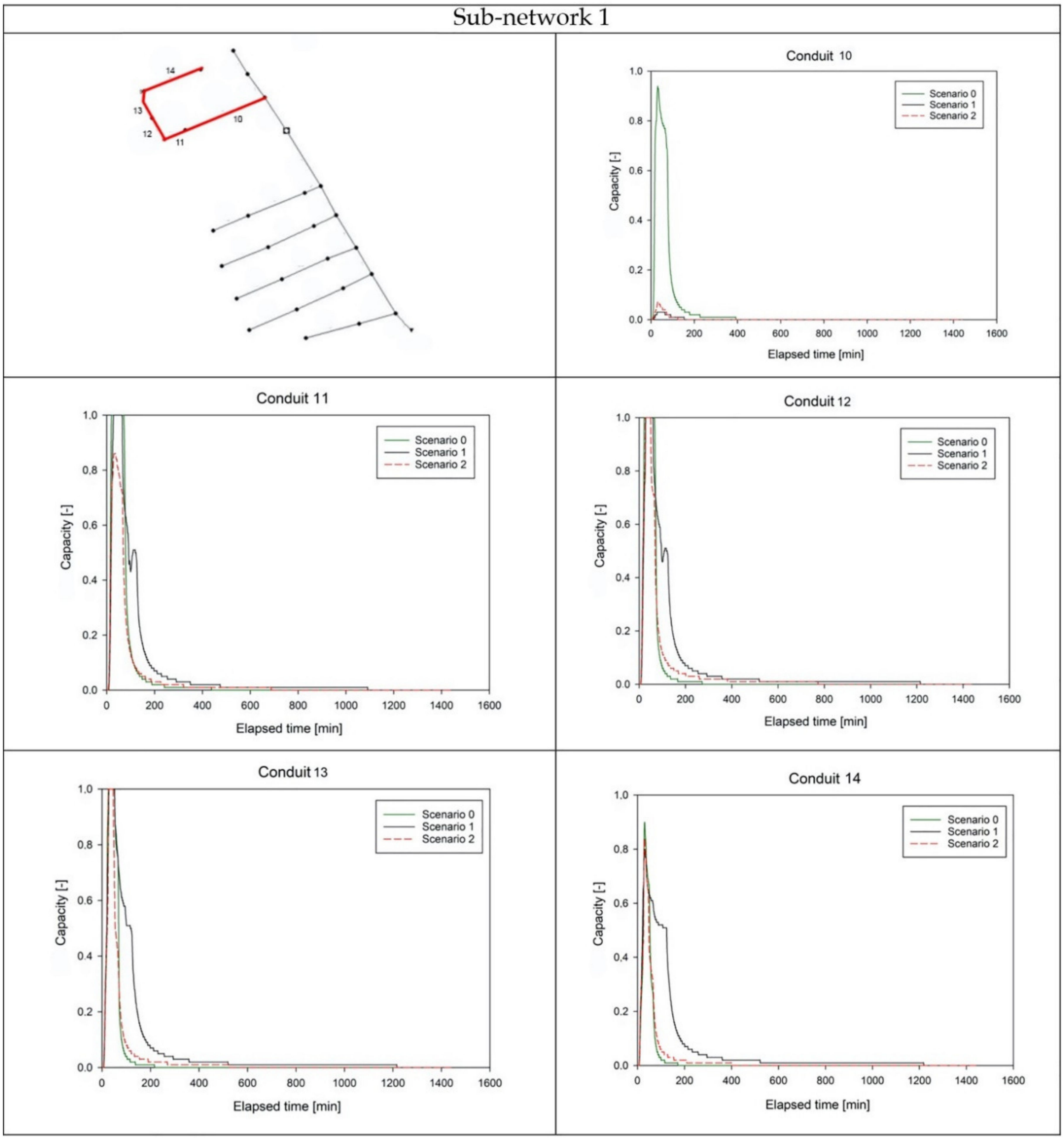

Figure A3. Conduits' capacity in sub-network 1, highlighted in red in the first picture where the drainage network schematization is shown.

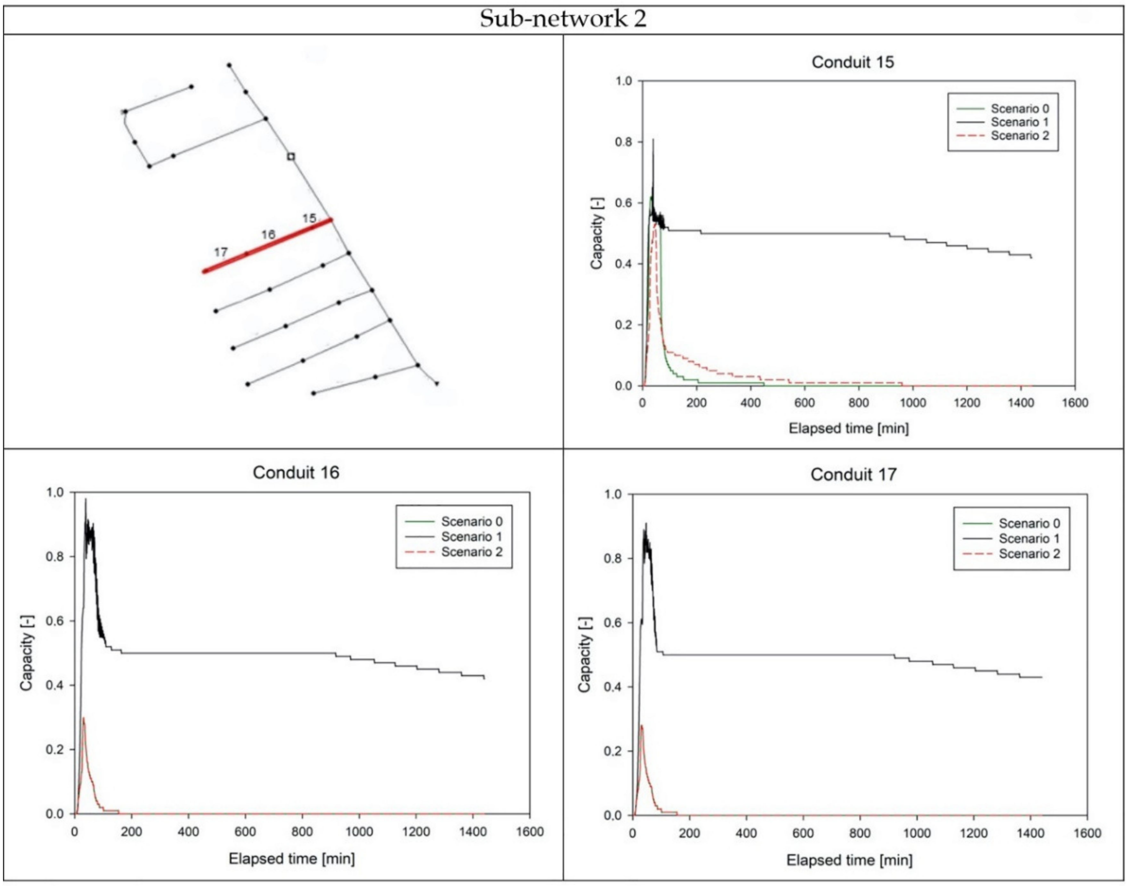

Figure A4. Conduits' capacity in sub-network 2, highlighted in red in the first picture where the drainage network schematization is shown.

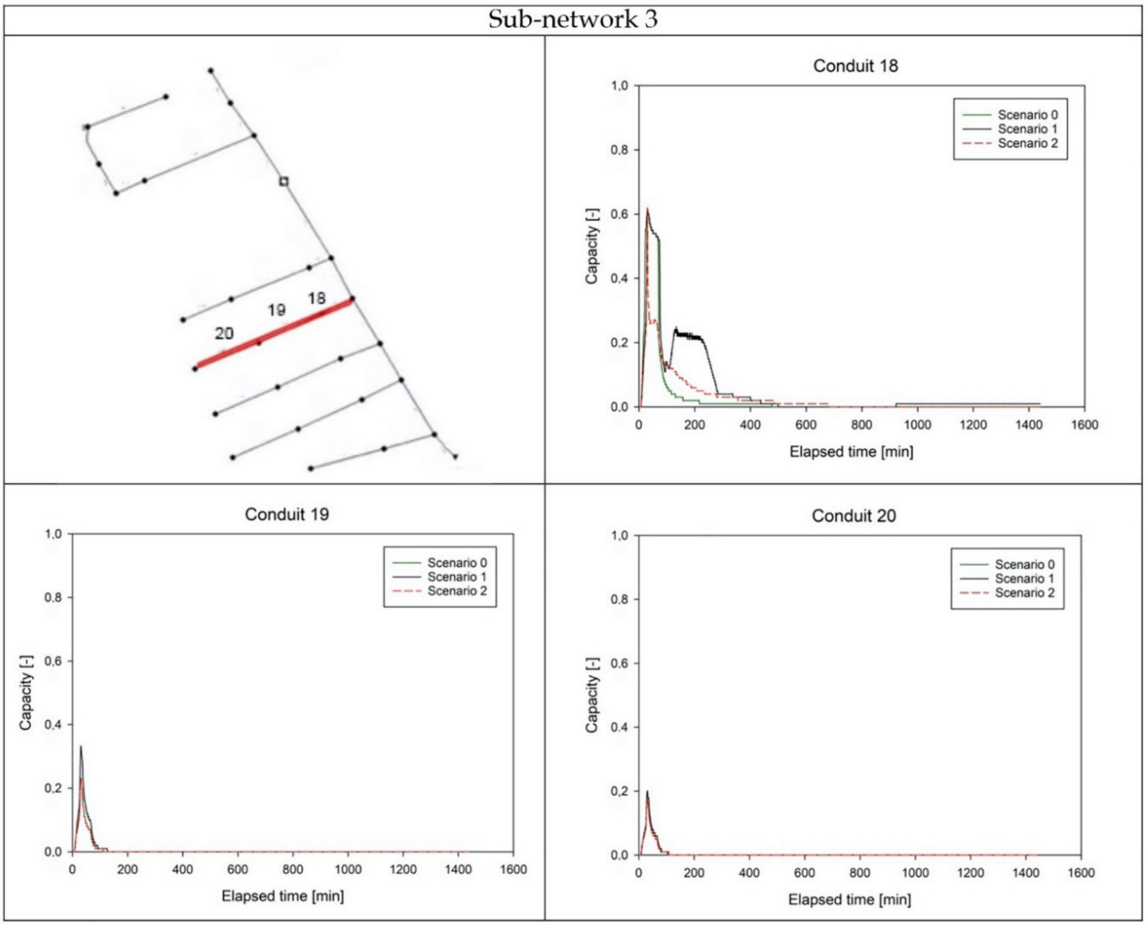

Figure A5. Conduits' capacity in sub-network 3, highlighted in red in the first picture where the drainage network schematization is shown.

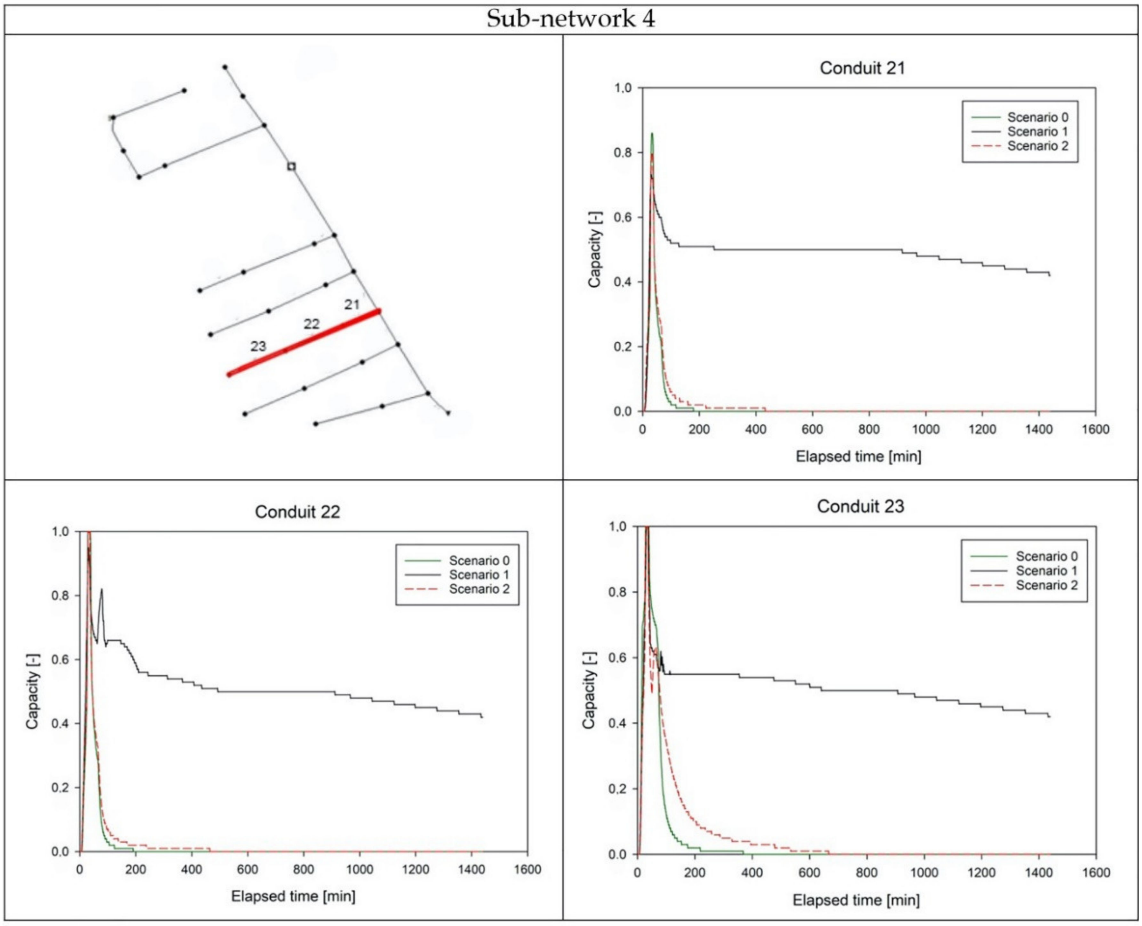

Figure A6. Conduits' capacity in sub-network 4, highlighted in red in the first picture where the drainage network schematization is shown.

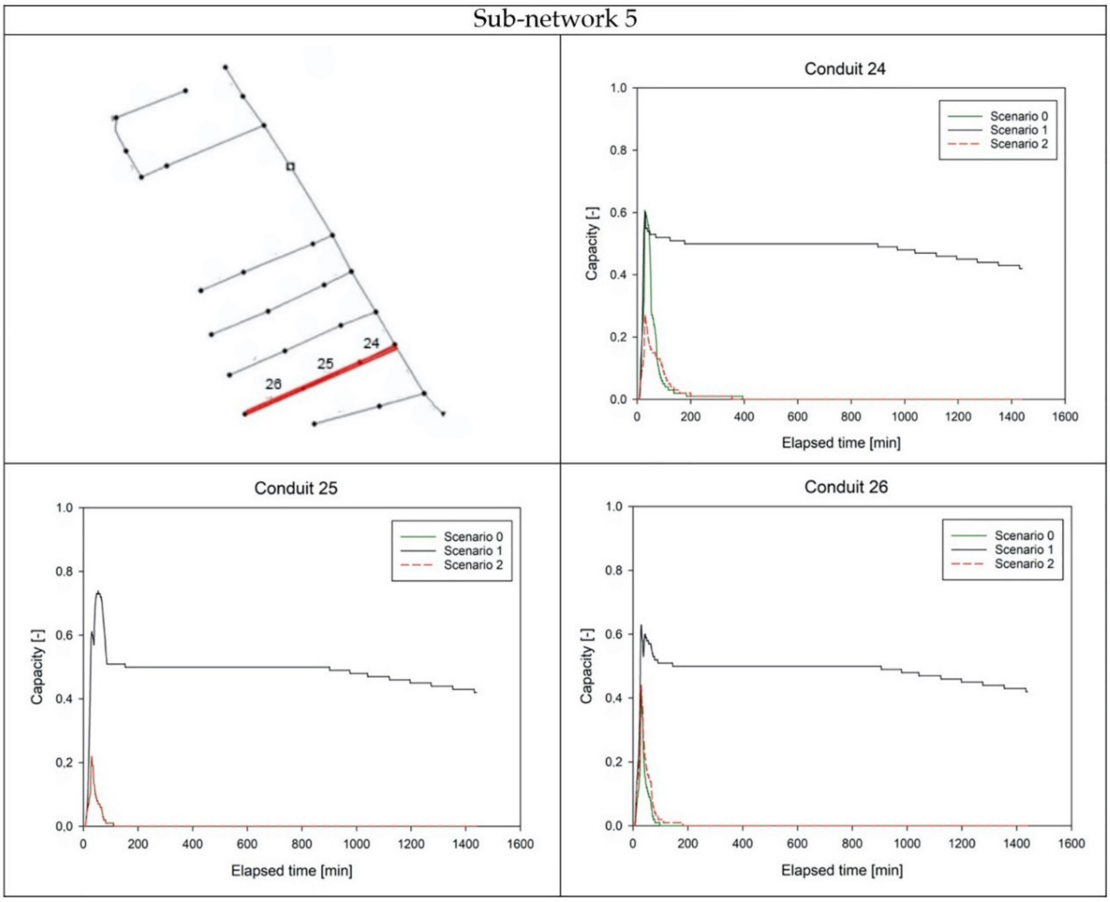

Figure A7. Conduits' capacity in sub-network 5, highlighted in red in the first picture where the drainage network schematization is shown.

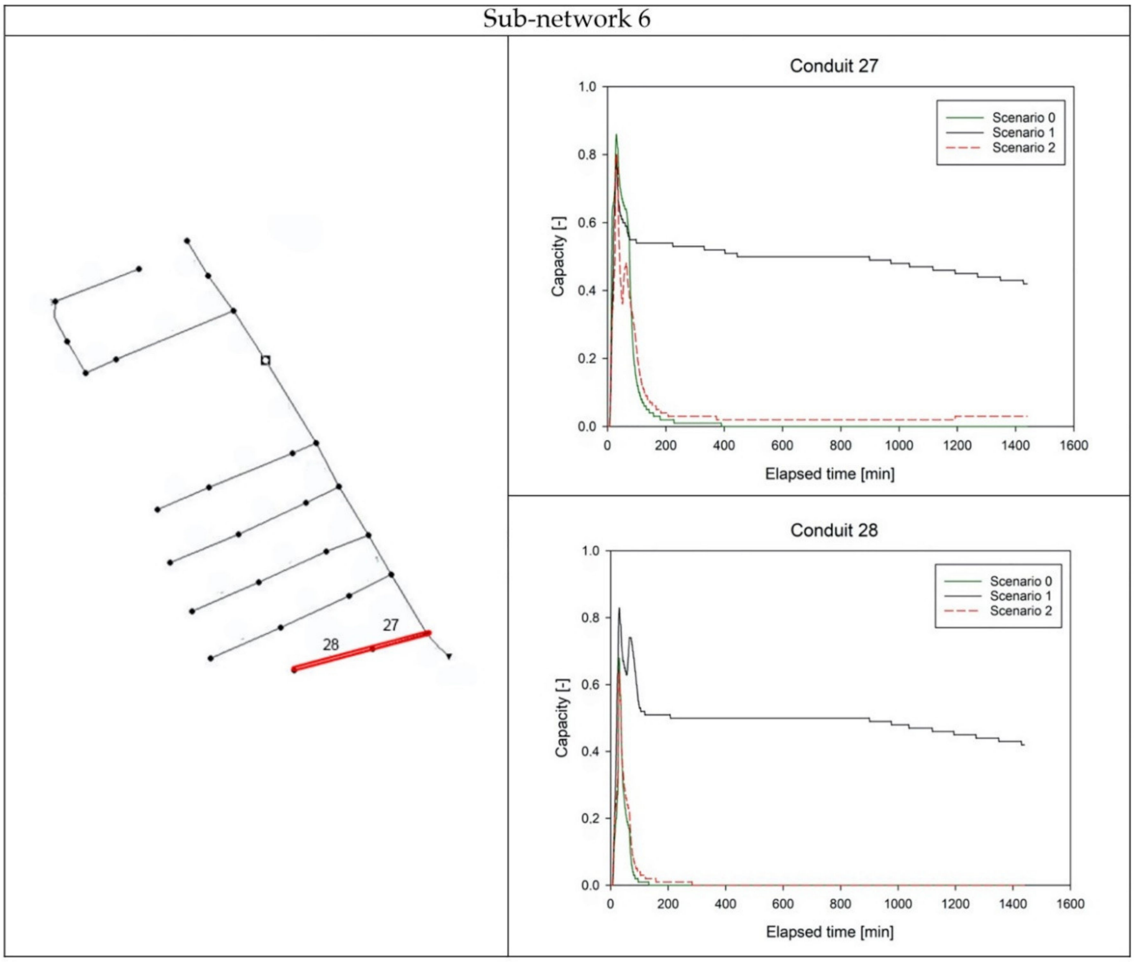

Figure A8. Conduits' capacity in sub-network 6, highlighted in red in the first picture where the drainage network schematization is shown.

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